

# Sustainable Energy Technologies and Assessments

## Performance of finned heat pipe assisted parabolic trough solar collector system under the climatic condition of North East India

--Manuscript Draft--

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<b>Abstract:</b>	The intermittent nature of solar radiation drives the researchers to store of solar energy using latent heat storage (LHS). In this work, an experimental investigation is carried out to study the performance of a heat pipe assisted parabolic trough collector (PTC) along with a paraffin wax based phase change material (PCM). The experiment has been performed under the climatic condition of North-East India. Further, a comparative assessment is done between the storage system with and without circular fins attached in the evaporator section of the heat pipe. The heat transfer characteristics during the charging/discharging process, temperature distribution, and energy stored in LHS are evaluated. The maximum average temperatures for PCM are estimated to be 63°C and 60°C with and without fins, respectively. The energy storage capacity of the LHS is around 330 kJ. The average charging efficiency of the LHS with fin configuration is 44.7% which is higher as compared to without fin configuration. The average discharging efficiency with fin configuration is 32.7%, higher than without fin configuration. Further, presence of fin in the evaporator system is found to reduce the energy pay back period of the thermal storage device.
<b>Suggested Reviewers:</b>	Behnaz Rezaie, PhD Assistant Professor, University of Idaho rezaie@uidaho.edu  Pradip Lingfa, PhD Professor, NERIST pradip.lingfa@gmail.com  Bale V Reddy, PhD Professor, Ontario Tech University: University of Ontario Institute of Technology Bale.Reddy@uoit.ca
<b>Opposed Reviewers:</b>	
<b>Response to Reviewers:</b>	Manuscript Number: SETA-D-20-01138 Title: Performance of finned heat pipe assisted parabolic trough solar collector system under the climatic condition of North East India Reviewer #1: The authors sincerely acknowledge the valuable inputs of the reviewer and wish to offer the following reply to the comments. Comment 1. Discuss the economical aspects related to addition of fins and the corresponding performance improvement. Reply to comment 1: Results indicate the presence of fin increase the average charging and discharging efficiency of the developed heat pipe embedded PCM based PTC almost 44.7% and 32.7% higher than the system without fin. Which clearly

indicate the importance of fin.

Further, in the revised manuscript an attempt has been made to incorporate the comparative economic analysis of both system in form of energy pay back time period (EPBT). Results indicate the developed PTC has an EPBT of around 7.8 and 7.4 years with and without fin, considering climatic conditions of the N-E India.

Comment 2. Discuss the role of weather conditions on the performance and results reported?

Reply to comment 2: The present experiment has been performed in the outdoor under the climatic condition of North-East India. Since the performance of any solar collector device depends on the respective metrological conditions of that place, thus the authors believe that the same setup will perform better for a place having higher no. of yearly sunny days or level of radiation. However, a typical effect of weather on the performance of solar device may be seen one of the earlier works of the authors (Gupta et. 2020). And for the present system this may be considered in future studies. Reference: A. Gupta, B. Das, J. D. Mondol, Experimental and theoretical performance analysis of a hybrid photovoltaic-thermal (PVT) solar air dryer for green chillies, Int. J. Ambient Energy (2020) 1 – 9.

Reviewer #2:

Authors would like express sincere thanks for the valuable comments.

Comment 1: Abstract is too general, you need to revise that. For example, the first three sentences are better to be moved to the introduction.

Reply to comment 1: As suggested by the reviewer the abstract is modified in the revised manuscript.

Comment 2: Please write the main novelty of this research at the end of the introduction as bullet items. You need to list the main four items.

Reply to comment 2: As suggested the novelty of the works are highlighted.

Comment 3- What are the uncertainties in your experiments?

Reply to comment 3: The uncertainties involved in the experiments are included in the manuscript.

Comment 4-The nomenclature part is not complete. Please revise.

Reply to comment 4: The nomenclature is updated in the revised manuscript.

Comment 5- The language should be improved, and long sentences should be split into some shorter ones. Check the whole manuscript sufficiently. The transition between sentences and paragraphs should be sharply improved. The authors are responsible to avoid grammatical errors and typos. There are many grammatical errors. If the authors could not resolve the language issue, I cannot recommend it for publication in the next round.

Reply to comment 5: The revised manuscript is updated by incorporating the possible grammatical corrections.

Comment 6-Try to highlight the novelty in the abstract, end of the introduction and conclusion. These parts are the main sections for showing the novelty of the work.

Reply to comment 6: Novelty of the paper is incorporated in the abstract, introduction and the conclusion parts.

Comment 7-The first sentence of the abstract should reflect the novelty of your work. The subsequent sentences should show the way of investigation, and the last part may describe the results of the study in both a qualitative and quantitative way. Eventually, you should finish the abstract using a conclusive sentence. Accordingly, the abstract should be rewritten. Also, please consider the length of the abstract which should not be lengthy.

Reply to comment 7: Abstract is updated as suggested by the reviewer.

Comment 8- Please update the references by adding new published papers. You may consider these or the PCM part:

Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles, International Journal of Heat and Mass Transfer 72, 690-703, Application of a ground source heat pump system with PCM-embedded radiant wall heating for buildings. International Journal of Energy Research 43

Reply to comment 8: The introduction is updated with the suggested papers.

To  
The Editor  
'Sustainable Energy Technologies and Assessment'

Date: 15/02/2021

Subject: Submission of Manuscript

Respected Sir,

Kindly find the attached revised manuscript, titled, '**Performance of finned heat pipe assisted parabolic trough solar collector system under the climatic condition of North East India**', for your kind consideration for publication your esteemed journal, 'Sustainable Energy Technologies and Assessment'.

Thanking you.

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# Performance of finned heat pipe assisted parabolic trough solar collector system under the climatic condition of North East India

Virendra Vishnu Bhagwat<sup>1</sup>, Sujit Roy<sup>1</sup>, Biplab Das<sup>1,2,\*</sup>, Nikhilkumar Shah<sup>2</sup>, Avijit Chowdhury<sup>3</sup>

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## Abstract

The intermittent nature of solar radiation drives the researchers to store of solar energy using latent heat storage (LHS). In this work, an experimental investigation is carried out to study the performance of a heat pipe assisted parabolic trough collector (PTC) along with a paraffin wax based phase change material (PCM). The experiment ha sbeen performed under the climatic condition of North-East India. Further, a comparative assessment is done between the storage system with and without circular fins attached in the evaporator section of the heat pipe. The heat transfer characteristics during the charging/discharging process, temperature distribution, and energy stored in LHS are evaluated. The maximum average temperatures for PCM are estimated to be 63°C and 60°C with and without fins, respectively. The energy storage capacity of the LHS is around 330 kJ. The average charging efficiency of the LHS with fin configuration is 44.7% which is higher as compared to without fin configuration. The average discharging efficiency with fin configuration is 32.7%, higher than without fin configuration. Further, presence of fin in the evaporator system is found to reduce the energy pay back period of the thermal storage device.

**Keywords:** *Parabolic trough collector; heat pipe; PCM; charging efficiency; discharging efficiency*

## 1. Introduction

The fossil fuels have witnessed higher consumptions because of the ever increasing energy demand during the last decade. The increased use of the fossil fuel resources, which are limited in nature, affects the environment and causes global warming. Therefore, it is necessary and important to utilize clean and renewable energy sources efficiently. Among other renewable energy sources, solar energy is the most promising option because it is a clean source of energy and abundantly available in nature [1]. Generally, the solar thermal collectors are used to capture solar energy for solar water heating systems, space heating systems, pool water heating systems, and absorption

cooling technological industry processes [2-4]. However, the solar-based technologies have few major disadvantages like their intermittent nature, less stability, and collection difficulties. Hence, there is an urgent need for thermal energy storage (TES) system based on solar energy systems which that can make the system more reliable.

The TES has the ability to store solar thermal energy and use it later when there is no solar irradiation [6]. The sensible, latent, and chemical are the forms of storing energy in TES. Among the TES systems, latent heat storage (LHS) has received much attention as it requires lesser volume to store thermal energy at an almost constant temperature. The thermo-physical properties of various available LHS materials are shown in Table 1. Among the TES systems, latent heat storage (LHS) receives more attention as it requires less volume, while storing thermal energy at an almost constant temperature. LHS systems are also used in electronic chip cooling systems, solar systems, air conditioning systems, refrigeration, waste heat recovery, and drying applications [9-13].

The present study is focused on the low temperature (<100°C) solar collector application. Paraffin is selected as an LHS material due to the suitable melting temperature range, negligible supercooling effect, and relatively high latent heat. The paraffin offers congruent melting property, i.e., melt and freeze repeatedly without any phase segregation [14]. Paraffin is also chemically stable, non-toxic, and non-corrosive, and does not have harmful effects besides certain disadvantages like flammable, non-compatible plastics and low thermal conductivity [15]. The low thermal conductivity can be overcome by introducing a number of methods to increase the heat transfer of LHS system, such as employing extended surfaces or fins [16], using multiple phase change material (PCM) [17], encasing the PCM in a structure of high thermal-conductive material such as graphite metal foil or foam [18]. Zhang and Faghri [19] have studied a PCM system with fins in the innermost tube and found that it can enhance the charging process. Stritih [20] has investigated experimentally by attaching fins into rectangular TES units results in 40% reduction in time for solidification. Choi and Kim [21] have shown the same results but this time storage is cylindrical and fins are attached radially. Khodadadi [22] has reviewed different thermal conductivity enhancement techniques for a faster phase change process by adding nanoparticles to PCM. Khodadadi and Hosseinizadeh [23] have studied the scattering particles with higher thermal conductivity in PCM, adding nano-particles to PCM, impregnating PCM with higher conductive porous materials. Hawlader et al. [24] have emphasized microencapsulation of PCM technique to enhance the rate of heat transfer in which liquid/solid PCM is kept in a



solid structure. Lee et al. [\[27\] have experimentally studied a LHS system employing different PCMs and a two-phase thermosiphon using ethyl-alcohol as working fluid.](#)

Another important technique that improves the heat transfer rate and resolves the fundamental challenges with LHS is heat pipe technology [25, 26]. Harikrishnan and Kotebavi [26] have found that the evaporation-condensation phenomenon in heat pipes is fully responsible for transferring heat rather than the conductivity of a material. Numerous researches have been reported in heat pipe assisted LHS. Similarly, Liu et al. [28] have developed a heat pipe (copper-water) based LHS system using paraffin wax and enclosing the heat pipe in the rectangular paraffin container. Shabgard et al. [29] have done a computational study of heat pipe assisted LHS units of two different configurations. Robak et al. [30] have compared the performances of the LHS system with and without heat pipe and fin. The results indicated that the melting is increased by almost 60%. Heat pipe combining metal foil is used by Sharifi et al. [31] to lessen the thermal resistance between working fluid of heat pipe and PCM. They [have](#) observed [the](#) improvement of melting and solidification rate in n-octadecane significantly. In another study, Liu et al. [32] [have](#) studied a dynamic charging process model of paraffin with heat pipe using R134a as working fluid and [have](#) found that heat storage rate and heat storage capacity [both are enhanced](#). Weng et al. [33] [have](#) performed [an](#) experimental study on PCM (tricosane) combining heat pipes and found that the cooling system results in 46% less consumption of fan power. Motahar and Khodabandeh [34] [have](#) experimentally visited the heat pipe assisted LHS system of n-octadecane to observe its melting and solidification characteristics. [The result indicates](#) that [the](#) melting and solidification rate [was](#) significantly increased by using heat pipes. [Oruc et al. \[35\] proposed PCM based latent heat TES using SP26E PCM for increase the thermal efficiency from 62% to 87% and exergy efficiency from 14% to 56%. Javani et al. \[36\] analysed the thermal management system using PCM's for obtaining more uniform temperature distribution about 10%.](#)

The literature [review](#) reveals that the heat pipe or fin [is considered](#) as one of the heat transfer techniques to increase the heat transfer rate in PCM. [However](#), the study of parabolic trough collector (PTC) with [combined](#) heat pipe and fins to enhance the PCM heat transfer rate has not been attempted in the past. [Further, performance of the heat pipe and PCM embedded PTC system in the climatic condition of North-East India is also scarce in literature.](#) In the present work, an experimental investigation is carried out to observe the performance of paraffin wax based LHS systems incorporating heat pipe and fin. Further, [the](#) performance of any solar-based system highly depends on the meteorological data of the locations. Performance of the PTC based system has also not been reported for

~~this~~the north-eastern region of India. Thus, the performance evaluation of heat pipe assisted LHS systems with and without fin is performed in the present study considering both in charging and discharging mode under the climatic condition of Silchar, Assam, India. The main contributions of the paper has been highlighted below:

- i. Performance of the heat pipe embedded phase change material (PCM) based solar parabolic trough collector (PTC) is presented with and without fin.
- ii. The experimental run is performed in the outdoor condition under climatic condition of North-East India.
- iii. Both charging and discharging efficiency is evaluated for the system including the melting fraction of the PCM.
- iv. Energy pay back period of both the system with and without fin is evaluated.

## 2. Materials and methods

Paraffin wax is a useful PCM material for low-temperature solar applications due to its low melting range (57-61 °C). Fig. 1 (c, d) shows the schematic diagram of the experimental arrangement and heat pipe with fins, respectively and the different position of the thermocouple are shown in Table 2. The thermo-physical properties of the PCM, working fluid inside the heat pipe, heat pipe, and fin are mentioned in Table 3. The major components which have been fabricated are a container for PCM filling and PTC. Due to higher thermal conductivity, copper is chosen as the suitable heat pipe material. Aluminum is used as the material to fabricate the PTC. An acrylic sheet of 0.003m thickness is used to fabricate the PCM container. An iron stand is used to support the fabricated setup. The dimensions of the PTC and PCM container, and the dimensions of the heat pipe are mentioned in Table 4 and Table 5, respectively. As shown in Fig. 1, an upright cylindrical enclosure made of acrylic is used to store the PCM (paraffin wax), of inner diameter  $\sim 0.064$  m, height  $\sim 0.21$  m, and wall thickness  $\sim 0.003$  m is filled with paraffin wax. To make the enclosure air-tight, approximately 0.006 m thick and 0.12 m diameter solid acrylic plates are fixed with flanges at both ends of the enclosure openings using nut and bolt. A hole of diameter  $\sim 0.018$  m is drilled in the bottom plate to insert the copper-water charged heat pipe into the enclosure. A heat pipe with length ( $L_{hp}$ ) and outer diameter ( $D_{hp}$ ) is 0.8 m and 0.016 m, respectively is used. The condenser section of length ( $L_c$ ) 0.2 m is embedded in PCM. The evaporator section is held outside the enclosure. The condenser section of the heat pipe has 40 aluminum circular fins attached to its outer circumference as shown in Fig. 1 (a). The fins are of 0.05 m outer diameter, 0.016 m inner diameter, and 0.001 m thickness. Thermal epoxy is used to attach the fins and condenser

section which reduces the thermal resistance at the interface. For ensuring an air-tight seal between the heat pipe and enclosure, a silicon adhesive is applied. This also helps the heat pipe to be in the predefined location. Once assembled, the enclosure is insulated with a 0.025 m thick layer of rockwool.

### 2.1. Uncertainty analysis

Uncertainty occurs due to the different types of errors involved in measuring any parameter. It indicates the consistency of the measured parameters. In the present experimental investigation, various parameters are measured using different instruments. Therefore, the calculation of uncertainties involved in measuring those quantities is required. The uncertainties in measuring flow rate, temperature, and solar radiation are found to be  $\pm 0.1\%$ ,  $\pm 0.25\%$ , and  $\pm 2.5\%$ , respectively. The range and error present in measuring instruments, and uncertainties are shown in Table 6.

### 2.2. Experimental procedure

The experiment includes two different modes i.e., charging (heat stored in PCM) and discharging (heat released from PCM). The PTC is used to concentrate the solar radiation on the heat pipe evaporator in the presence of solar energy. The concentrated heat absorbed by the evaporator vaporizes the working fluid in the heat pipe. The vapor flows towards the heat pipe condenser due to pressure difference and returns to the liquid phase by rejecting heat to PCM. Thus, the heat energy from the solar radiation is transmitted to the PCM and is stored there. During this charging process, the temperatures are measured at evaporator and condenser sections of the heat pipe, and at the various local position in PCM. The solar radiation and ambient temperature are recorded during the experiment. Water is supplied at the heat pipe condenser through capillary tubes during the discharging process and temperatures are measured at inlet and outlet of water. Finally, the melting fraction during melting/solidification, heat stored/released, percentage efficiencies are calculated both for charging and discharging process.

### 2.3 Mathematical formulation

The solar energy absorbed at the evaporator is transferred to the condenser with the help of evaporation-condensation phenomena. Then, the heat flux is absorbed by the PCM filled in the container and release that stored heat to water during discharging.

In the present experiment, the following assumptions are supposed:

- Material properties are isotropic in nature.
- Quasi-steady state condition is maintained during heat transfer.
- Lengthwise axial conduction in heat pipe is neglected.

- Uniform temperature at evaporator ( $T_{hp,e}$ ) and condensation ( $T_{hp,c}$ ) section.

The storage capacity of LHS system can be calculated using Eq. (1-2) [37]

$$q_{pcm} = \int_{T_i}^{T_m} m_{pcm,s} \cdot C_{sp} \cdot dT + F_{melt} \cdot m_{pcm,l} \cdot L_{pcm} + F_{melt} \cdot \int_{T_m}^{T_f} m_{pcm,l} \cdot C_{lp} \cdot dT \quad (1)$$

$$q_{pcm} = m_{pcm,s} \cdot C_{pcm,s} \cdot (T_m - T_i) + F_{melt} \cdot m_{pcm,l} \cdot L_{pcm} + F_{melt} \cdot m_{pcm,l} \cdot C_{pcm,l} \cdot (T_{pcm} - T_m) \quad (2)$$

$$\text{where, } F_{melt} = \frac{T_{pcm} - T_L}{T_S - T_L} \quad (3)$$

The heat transmitted from evaporator to condenser section of heat pipe is calculated using Eq. (4);

$$\dot{q}_{hp} = (T_{hp,e} - T_{hp,c}) / R_{hp} \quad (4)$$

where  $R_{hp}$  is overall thermal resistance posed by heat pipe as shown in Fig. 2 and can be determined by Eq. (5) [38,39]

$$R_{hp} = R_{hp,e,p} + R_{hp,e,w} + R_{hp,i} + R_{hp,c,p} + R_{hp,c,w} + R_{hp,c} \quad (5)$$

where, container wall resistance (evaporator),

$$R_{hp,e,p} = \frac{\ln(d_o/d_i)}{2\pi L_e k_p} \quad (6)$$

Wick conduction resistance(evaporator),

$$R_{hp,e,w} = \frac{\ln(d_{o,w}/d_{i,w})}{2\pi L_e k_{eff}} \quad (7)$$

Internal resistance (vapor-liquid interface),

$$R_{hp,i} = \frac{2t_w}{\pi k_l d_i L_e} \quad (8)$$

Container wall resistance(condenser),

$$R_{hp,c,p} = \frac{\ln(d_o/d_i)}{2\pi L_c k_p} \quad (9)$$

Wick conduction resistance(condenser),

$$R_{hp,c,w} = \frac{\ln(d_{o,w}/d_{i,w})}{2\pi L_c k_{eff}} \quad (10)$$

Thermal resistance (condensing process),

$$R_{hp,c} = \frac{1}{\pi h_{con} d_i L_c} \quad (11)$$

Condensing film coefficient,

$$h_{con} = 0.728 \left[ \frac{g \rho_l (\rho_l - \rho_v) k_i^3 h_{fg}}{d_i \mu_l T_i} \right]^{1/4} \quad (12)$$

Heat recovered from PCM during discharging by water can be computed from Eq. (13) [35]

$$\dot{q}_w = \sum \dot{m}_w \cdot C_{p,w} \cdot (T_{w,out} - T_{w,in}) \quad (13)$$

The heat storage efficiency (charging efficiency) and heat release efficiency (discharging efficiency) can be calculated using Eq. (14,15) [37]

Charging efficiency,  $\eta_{pcm}$

$$\eta_{pcm} = \frac{\text{Total heat energy stored by PCM}}{\text{Total solar energy incident on the parabolic collector}}$$

$$\eta_{pcm} = \left( \frac{q_{pcm}}{\bar{I} \times A_{PTC} \times \text{Total Time}} \right) \times 100\% \quad (14)$$

where,  $A_{PTC}$  = effective parabolic trough collector area.

Discharging efficiency,

$$\eta_{water} = \frac{\text{Total heat energy recovered by water}}{\text{Total heat energy stored in PCM}}$$

$$\eta_{water} = \left( \frac{\sum \dot{q}_w}{q_{pcm}} \right) \times 100\% \quad (15)$$

### 3. Results and discussion

The experiments are conducted in the composite climatic condition of North-East India (Silchar having latitude 24.83 °N and longitude 92.77 °E). The results and discussion section is divided into two different segments i.e., charging process and discharging process. The local and average temperature of PCM, melt fraction of PCM, stored/released energy in PCM is discussed both for the charging and discharging process. A comparative study is performed to evaluate the effect of the fin. Further, the charging and discharging efficiency of the LHS system are also discussed. The variation of solar radiation and ambient temperature on the day of the experiment, as shown in Fig. 3, are for consecutive two days. A similar trend is also observed for the same location as reported in ref. [40, 41]. The maximum ambient temperature of 35°C is observed around 13:00 and 12:45 hr, whereas, the maximum solar radiation is observed to be 1111.0 and 1084.0 W/m<sup>2</sup> at 12:15 and 12:30 hr, respectively.

### 3.1. Charging Mode

In the charging process, the solar energy from the PTC is received by the heat pipe (evaporator) and transferred to the condenser section, where that heat is released to the PCM to store.

#### 3.1.1. Temporal variation at heat pipe section

Figure 4 represents the variation of the wall temperature at the evaporator and condenser section of the heat pipe with time. The result demonstrates that the temperature differences between the condenser and evaporator (T5-T6) go upto 20 °C which starts increasing with the intensity of solar radiation. At the very beginning of the charging process, the transmission of heat from the PTC collector to the heat pipe evaporator is primarily utilized to heat the wall of the heat pipe and this progression takes about an hour. When the temperature of the heat pipe condenser section is greater than the PCM temperature, the transfer of heat between the PCM and the heat pipe is initiated. It is observed that after 14:00 hrs the difference in temperature between the condenser and evaporator sections starts decreasing due to the reduction of solar radiation. The temperature differences between the condenser and evaporator sections are further decreased as time progresses. The maximum temperatures at the evaporator and condenser section are recorded as 86°C and 67°C, respectively.

#### 3.1.2. Variation of PCM temperature

The variation of PCM temperature at four different positions throughout the day with and without fins- is shown in Figure 5. Initially, the thermal energy received by the PCM is used to raise its temperature and acts as a sensible form of energy storage. The heat energy transferred to the PCM is purely by conduction and the temperature of the PCM increases almost linearly. When the PCM temperature reaches solidus temperature (also known as lower melting temperature), PCM starts to melt. The PCM temperature near the condenser section rises very quickly due to the exchange of heat. It is to mention here that RTDs near ~~to~~ the condenser section of the heat pipe (T2 and T3) are showing the highest local temperatures for both the setup with and without fins. However, the PCM temperature becomes almost constant when it starts to melt due to energy stored as latent heat (heat storage at almost constant temperature). In the same way, heat is stored in the form of sensible heat after the melting of PCM. Thus the different trends in temperature variation of the PCM are observed. During the process of melting, the convection dominates over the conduction because of the density gradients within the liquid PCM. However, the conduction

becomes negligible when the PCM melts completely. It is observed that the highest local PCM temperature is 63.9°C with fins and 61°C without fins measured at 15.00 hrs. The maximum average PCM temperature achieved with a fin system is 63°C, whereas, without fins, it is found as 60°C as shown in Fig. 5-(c). Therefore, there is a 5% increment in maximum average PCM temperature with fin system compared to without fin system.

### 3.1.3. Variation of melt fraction

Figure 6 (a-c) represents the local and average melt fraction of the storage system during the charging process with and without fins. The local melt fraction of the PCM is calculated by measuring the temperature of PCM at four different locations and using Eq. (3). Melt fraction remains zero before the PCM reaches its solidus temperature. It takes about 3 hours for PCM to attain an average melt fraction of unity. The results indicate that PCM at the vicinity of the heat pipe starts melting first then the rest follows with time, and the trend is the same for both the systems with and without fin. This is due to the lower thermal conductivity of the PCM. It can also be noted from the plot that the rate of increase of melt fraction at the bottom portion of the container is slow as compared to the top portion. This can be explained by the fact that as the PCM melts at the bottom it rises towards the top and assists the melting of the PCM at the top. Further, it can be observed from Fig. 6 (c) that the average melt fraction with fins system is zero-till 09:15 hr after that the average melt fraction started increasing at a constant rate till 12:45 hr. For the next 15 minutes, the melt fraction remains constant due to a decrease in the level of solar radiation. After that, the melt fraction starts increasing and reaches unity at 13:30 hr. Whereas, in the system without fins, the melting starts after 10.30 hrs and completes by 15.00 hr. Thus fins can be used to assist the melting process of PCM. The melt fraction rate of the PCM with fin system is 28% higher than the melt fraction rate of the PCM without fin system.

### 3.1.4. Variation of energy stored

Figure 7 shows the variation of energy stored in the LHS system with and without fins. The circular container is designed to store latent and sensible heat of 240 kJ and 90 kJ, respectively, and it is calculated using Eq. (2). When the solar energy incident occurs on the PTC collector, the heat is absorbed by the heat pipe and conveyed and stored within a circular container containing PCM. It can be noticed that the maximum energy stored in the system is 330 kJ. At the start of the experiment, PCM is in solid-state (28° C) and the heat is stored in the form of sensible energy until the temperature rises upto 58° C. Then PCM starts melting and the mode of stored energy becomes latent heat. Once the fraction of the whole PCM melts then again it starts storing heat in the form of sensible mode. The amount

of total, latent, and sensible energy stored in the TES system is 330 kJ, 90 kJ, and 240 kJ, respectively. The results also indicate that the magnitude of latent heat stored is zero until 09:15 hr for the system with fin and 10.30 hr for system without fin. It can also be seen that after 13:15 hr with the fin system there is no increment in the latent energy storage of the system which indicates that the PCM is completely melted. Whereas, the system without PCM stores latent heat till 15.00 hrs. Therefore, it can be observed that the addition of fins can enhance the heat storage process and be able to store more energy in less duration. Total energy stored follows the same trend as that of the average temperature and melt fraction.

### *3.2. Discharging mode*

The heat energy stored by the PCM is recovered by allowing the water to flow over the heat pipe at 1 LPH. The discharging process starts at 16:00 hr in the afternoon and the inlet temperature of the water is in the range of 23-24 °C. The discharge period is selected considering two reasons: (i) to maximize the system capability for hot water production, and (ii) when ETSC failed to transfer heat energy to the TES manifold due to a lower level of solar radiation. The graphical plot illustrates the behavior of the TES system in delivering the stored heat energy. PCM loses the sensible heat very quickly as compared to latent heat. The effect of fins on the PCM temperature, melting process, and energy released by storage is discussed in this section.

#### *3.2.1. Variation of PCM temperature*

Figure 8 (a-c) represents the variation of the local and average PCM temperature with time during the discharging process with and without fins. The temperature measurements made at the four sections of the TES acrylic container are compared. From Fig. 2 (c) it is revealed that the temperature of the PCM decreases very fast as the PCM loses its stored sensible heat energy very fast. The PCM temperature in the vicinity of the heat pipe in the TES acrylic container is decreased faster than the PCM near the container boundary surface. The higher temperature difference between the heat pipe condenser section and the PCM is the reason for the same. When the thickness of solidified PCM increases around the heat pipe and fins, the rise in PCM temperature becomes negligible. As the PCM near the heat pipe solidifies first, solid PCM reduces the heat transfer from the liquid PCM to the heat pipe condenser due to low thermal conductivity. It can be observed that discharging starts at 16.00 hr and gets completely discharged by 19.15 hr and 20.00 hr with and without fins, respectively. Thus, fins can help in the quick discharging of energy from the PCM.



### 3.2.2. Variation of melt fraction

Figure 9 (a-c) shows the variation of melt fraction (local and average) of the TES system. The local melt fraction has been calculated by measuring the temperature of PCM at four different locations. It can also be observed that PCM at the vicinity of the acrylic container is started to solidify first which is then followed by the PCM away from the heat pipe. The average melt fraction of the PCM is calculated by taking the arithmetic mean of the local melt fraction at four different locations. Results indicate that the PCM solidifies completely at 18.00 hr and 18.30 hr with and without fin, respectively. A close look into the results indicate that average discharging rate is higher for the TES with fin. However, at the beginning, TES with fin shows lower rate of discharge under similar flow rate of water. This may be due to higher storage capacity of the TES system with fin under the similar solar radiation as that of TES system without fin. Further, higher discharging rate for the TES with fin may also be attributed to the additional area extended by the fin. As for the TES system without fin, once the paraffin starts solidifying it lower the transfer of heat from the paraffin available away from the heat pipe, due to lower conductivity of the paraffin.

### 3.2.3. Variation of energy discharged

The energy (sensible, latent, and total) storage of the TES system during the discharging process with and without fins is shown in Fig. 10. Once the intensity of the solar radiation reaches its minimum value, the PTC collector provides zero input energy condition and after that dripping water with a constant flow rate at the evaporator section heat pipe. The initial temperature of the PCM with the fin system is higher than the phase change temperature ( $63.15^{\circ}\text{C}$ ), which indicates that the system is fully charged and the melt fraction is unity. For the system without fin, the temperature of the PCM is just near to the phase change temperature ( $60.12^{\circ}\text{C}$ ), which indicates that the system is fully charged but lesser heat energy is stored as compared to the system with fin. From the figure, it can be observed that the PCM starts releasing latent heat at 16:30 hr and 16:15 hr with and without fins, respectively. Due to extra heat stored in the fins, initially, the system without fins starts releasing latent heat earlier than the system with fins. It is observed that after a certain time PCM starts to solidify and both the latent and sensible heats are discharged from the system. It can also be seen that after 18:00 hr there is no increment in the latent energy storage of the system with fins, whereas, a system without fins releases latent heat till 18.30 hr. The system with fin is able to discharge the stored heat completely by 19.15 hr, whereas, the systems without fins are able to get fully discharged by 20.00 hr. The complete cycle (charging + discharging) of energy stored in PCM during the

entire day with and without fins can be seen in Fig. 11. It can be observed that charging is completed and discharging is started by 16:15 hr. When the solar radiation is available, the LHS system stores heat energy in the form of latent heat and sensible heat energy. Energy storage by the PCM increases with time when solar radiation is incident on the collector. Figure shows that the duration of discharge is less than the duration of charging. The charging process takes about 8 hrs to get fully charged the TES system and takes about 4 hrs to get fully discharged. Once the average PCM temperature reached around 28°C at 20:00 hr, the amount of discharged total, latent and sensible energy from the TES system is 315 kJ, 75 kJ, and 240 kJ, respectively. This is because during discharging heat energy is not only released to the water but also there is some energy loss to surroundings due to the temperature difference. Therefore, PCM takes more time to get charged during the charging process relative to the time needed to release the energy during the discharging process.

### 3.3. Variation of efficiencies

The variation of the charging efficiency of the LHS system as a function daytime is shown in Fig. 12 (a). The charging efficiency increases with time and reaches a maximum during noon and then shows a declining trend. This follows the solar radiation trend which is one of the predominant factors affecting charging efficiency. The losses during morning time are higher in comparison to that of the evening. It has been observed that the trend of charging efficiency with the fin is higher than without fin. It may be observed from the trend that between 9.30 hr – 11.30 hr, the efficiency with the fin is slightly steady due to the storing of latent heat during that period and it is noticed that PCM in the vicinity of the fin melted fully by 11.30 hr. Then this melted PCM helps to melt the PCM near the wall of the container. After 13:00 hr, the PCM inside the LHS system is fully melted and at the same time, solar radiation also starts reducing resulting in efficiency reduction. After 14:00 hr, the PCM inside the LHS system is fully melted and it starts storing the sensible heat. The results indicate that the average charging efficiency of the system with fin configuration is 44.72% higher in comparison to without fin configuration. Similarly, Fig. 12 (b) shows the discharging efficiency of the LHS with and without fin. The discharging efficiency of LHS with and without fin are also observed and found to reduce with time. Initially, the discharging efficiency is higher due to the higher convection heat transfer coefficient in the heat pipe and the PCM, which enhances the discharging rate. As The PCM starts losing its energy at 17:00 hr the PCM around the fin solidifies and decreases the heat transfer rate. The system without fin is discharged slowly as compared with fin because the heat-release rate of the PCM is limited, which is mainly due to PCM's low thermal conductivity. Further, the presence of fin allows rapid discharge,

and reduce the discharging time by almost one hour. The discharging efficiency of 61.27% and 57.57% are observed with and without fins, respectively, at a mass flow rate of 1 LPH. The average discharging efficiency of the LHS is found to be 32.68% higher with fin.

#### 3.4. Energy payback period of the developed system

The embodied energy is the input energy required in production of raw materials to develop any system. It takes into account the total total consumption during the raw material to the final product and is calculated by the total energy density of each component times total mass of material used [42]. The distribution of embodied energy to fabricate the current developed system is mentioned in Table 7. The calculated embodied energy is used to calculate the energy payback time (EPBT). EPBT is the ratio of embodied energy (energy input) to the energy gained from the system (output energy) and it gives a measurement of the time required to pay back the expenses incurred in fabricating current system [42]. EPBT is found to be 7.4 years and 7.8 years incase of system without fin and system with fin, respectively. The higher payback time required in the system with fin is due to the extra costs incurred due the attachment of fin. But it is countered by the fast charging and discharging ability of the system with fin.

#### 4. Conclusions

Heat pipe based latent heat storage (LHS) is experimentally investigated with and without aluminum fins under the climatic conditions of North East India. This study also utilizes the advantages of a parabolic trough collector to concentrate the diffused solar radiation over a smaller area.

- The melt fraction rate of the PCM with fin system is 28% which is higher than the melt fraction rate of the PCM without fin system.
- The charging process takes 8 hrs to get fully charged the TES system and takes 4 hrs to get fully discharged. Further, presence of fin incarese both the charging and discharging rate.
- PTC increases the solar insolation density which helps to increase the charging rate by 81%.
- The presence of fin improves the average of the LHS by as high as.
- The average charging and discharging efficiency of the LHS with fin configuration is found to be 44.7% and 32.7% higher than the system without fin.

- The maximum charging and discharging efficiency of the LHS are found to be 67.6% and 61.3%, respectively, with fin configuration, whereas, the maximum charging and discharging efficiency of the LHS is found to be 51.7% and 57.6%, respectively, without fin configuration.
- Energy pay back period of the developed TES is found to be 7.8 years and 7.4 years with and without fin, respectively.

Thus, it can be concluded that, the compact design leads to very less heat energy ruin in the system. Therefore, by using PCM, heat pipe, and fin, could be helped to achieve the highest possible thermal efficiency in converting solar energy to get hot water.

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## Nomenclature

$C_{p,l}$	Specific heat of liquid PCM (J/kg.K)
$C_{p,s}$	Specific heat of solid PCM (J/kg.K)
$C_{p,w}$	Water Specific heat (J/kg.K)
$C_f$	Specific carbon content in the fuel [ $\text{kg}_c/\text{kg}_{\text{fuel}}$ ]
$d_i$	Inner wall diameter of the heat pipe (m)
$d_o$	Outer wall diameter of the heat pipe (m)
$d_{o,w}$	Outer diameter of wick wall (m)
$d_{i,w}$	Inner diameter of wick wall (m)
$F_{\text{melt}}$	Molten PCM fraction (-)

$g$	Acceleration due to gravity ( $m/s^2$ )
$h_{fg}$	Latent heat of vaporization ( $J/kg$ )
$H_f$	Specific energy content in the fuel [ $kwh/kg_{fuel}$ ]
$k$	Thermal conductivity ( $W/mK$ )
$k_{eff}$	The effective thermal conductivity of the wick ( $W/mK$ )
$L_{pcm}$	Latent heat of PCM ( $J/kg$ )
$m_{pcm}$	Mass of PCM ( $kg$ )
$m_w$	Water mass flow rate ( $kg/s$ )
$M_m$	Molecular weight Carbon [ $kg/kmol$ Carbon]
$M_{CO_2}$	Molecular weight Carbon Dioxide [ $kg/kmol$ $CO_2$ ]
$q_{hp}$	Heat transferred from HPE to HPC ( $J/kg$ )
$Q_{CO_2}$	Heat recovered from PCM during discharging
$q_w$	Specific $CO_2$ emission [ $kg_{co_2}/kwh$ ]
$q_{pcm}$	Heat energy stored in PCM ( $J/kg$ )
$R_{hp}$	HP overall thermal resistance ( $K/W$ )
$T_a$	Ambient temperature ( $^{\circ}C$ )
$T_f$	Final temperature of PCM ( $^{\circ}C$ )
$T_{hp,e}$	Surface temperature of the evaporator section of the heat pipe ( $^{\circ}C$ )
$T_{hp,c}$	Surface temperature of condenser section of the heat pipe ( $^{\circ}C$ )
$T_i$	Initial temperature of PCM ( $^{\circ}C$ )
$T_m$	Melting temperature of PCM ( $^{\circ}C$ )
$T_{pcm}$	The average temperature of PCM ( $^{\circ}C$ )
$T_{PCM}$	Mean temperature of PCM in the container ( $^{\circ}C$ )
$t_w$	Wick thickness ( $m$ )
$T_{w,in}$	Inlet water temperature ( $^{\circ}C$ )
$T_{w,out}$	Outlet water temperature ( $^{\circ}C$ )



## Greek symbol

$\rho_l$	Liquid water density (kg/m <sup>3</sup> )
$\rho_v$	Water vapour density (kg/m <sup>3</sup> )
$\mu_l$	Dynamic viscosity of liquid water (N-s/m <sup>2</sup> )
$\eta$	Efficiency (-)

## Subscript

c	Condenser
e	Evaporator
eff	Effective
i	Inner wall, initial
l	Liquid phase
v	Vapour phase
w	Wick material

## Abbreviation

HP	Heat pipe
HTF	Heat transfer fluid
LHS	Latent heat storage
PCM	Phase change material
PTC	Parabolic trough collector
TES	Thermal energy storage

**Lists of Table and figure caption:**

**Table 1.** Thermo-physical properties of different low temperature PCM [7, 8]

**Table 2.** Thermocouple locations

**Table 3.** Thermal properties of PCM, heat pipe and fin [38]

**Table 4.** PTC and PCM container dimensions

**Table 5.** Heat pipe dimensions

**Table 6.** Uncertainties in measured parameters

**Table 7.** Break down of the embodied energy for the components used in the TES

**Fig. 1** Experimental setup of the LHS prototype (a) PCM container with fins and (b) insulated condenser and PCM container (c) schematic of experimental setup (d) schematic of heat pipe combining circular fins

**Fig. 2** Thermal resistance network of a typical heat pipe

**Fig. 3** Solar radiation and ambient temperature for Silchar, Assam

**Fig. 4** Temperature variation at heat pipe condenser (HPC) and evaporator (HPE)

**Fig. 5** Temperature variation of PCM at different positions during charging (a) with fin and (b) without fin (c) average PCM temperature with and without fin

**Fig. 6** Local melting fraction of PCM during charging (a) with fin and (b) without fin (c) average melting fraction with and without fin

**Fig. 7** Rate of energy storage in LHS during charging with and without fins

**Fig. 8** Temperature variation of PCM at different positions during discharging (a) with fin and (b) without fin (c) average PCM temperature with and without fin

**Fig. 9** Local melting fraction of PCM during discharging (a) with fin and (b) without fin (c) average melting fraction with and without fin

**Fig. 10** Rate of energy recovered from LHS during discharging

**Fig.11** Stored heat in PCM during complete charging-discharging cycle

**Fig. 12.** Variation of Charging and discharging efficiency of LHS system

Table 1.

Type of PCM	Melting point [°C]	Melting enthalpy [kJ/kg]	Thermal conductivity [W/m K]	Density [kg/m <sup>3</sup> ]
Sodium (Na)	97	113	71	968 (solid) 850 (liquid)
Paraffin wax	64	173.6	0.167 (liquid, 63.5 °C) 0.346 (solid, 33.6 °C)	916(24 °C) 790 (65 °C)
Tetracosane (C <sub>24</sub> H <sub>50</sub> )	50.6	255	-	799 (liquid)
Oktacosane (C <sub>28</sub> H <sub>58</sub> )	41.2	254	-	806 (liquid)
Capric acid (C <sub>10</sub> H <sub>20</sub> O <sub>2</sub> )	32	152.7	0.153 (liquid at 38.5°C)	1004 (solid, 24°C), 878 (45°C)
Lauric acid (C <sub>12</sub> H <sub>24</sub> O <sub>2</sub> )	42	171	-	870 (liquid)
Palmitic acid (C <sub>16</sub> H <sub>32</sub> O <sub>2</sub> )	64	185.4	0.162 (liquid at 68.4°C)	989 (24°C), 850 (65°C)
Stearic acid (C <sub>18</sub> H <sub>36</sub> O <sub>2</sub> )	69	209	-	940 (liquid)
Ethylene glycol	63.2	215.8	-	-
Methyl-12-hydroxystearate	43	126	-	-

Table 2.

<b>Thermocouple</b>	<b>r-Coordinate (m)</b>	<b>z-Coordinate (m)</b>
<b>T1</b>	-0.024	0.651
<b>T2</b>	0.015	0.687
<b>T3</b>	-0.015	0.723
<b>T4</b>	0.024	0.759
<b>T5</b>	0.008	0.7
<b>T6</b>	0.008	0.173

Table 3.

Property	PCM	HP Working Fluid	HP	Fin
Material	Paraffin Wax	Water	Copper	Aluminum
Density (kg/m <sup>3</sup> )	990(solid)	996.6(liquid)	8933	2702
	916(liquid)	0.554(vapour)		
Thermal conductivity (W/mK)	0.349(solid)	0.6132(liquid)	401	237
	0.167(liquid)	0.01932(vapour)		
Specific heat, (kJ/kgK)	2.76(solid)	4.18(liquid)	0.385	0.903
	2.48(liquid)	1.882(vapor)		
Latent heat, (kJ/kg)	208	2434.9	-	-
Viscosity, (Pa s)	3.09 x 10 <sup>-3</sup>	8.614 x 10 <sup>-4</sup> (liquid)	-	-
		0.09174x10 <sup>-4</sup> (vapour)		

Table 4.

<b>Parabolic Trough Collector</b>		<b>Dimensions</b>
Equation of Parabola	$Y = \frac{X^2}{80}$	
Aperture Area		0.6 x 0.2 m <sup>2</sup>
Concentration Ratio		12.5
<b>Container for PCM</b>		
Container material		Acrylic
Outer Diameter		0.070 m
Inner Diameter		0.064 m
Wall Thickness		0.003 m
Container Length		0.21 m

Table 5.

<b>Heat pipe geometrical features</b>	<b>Length (m)</b>
Evaporator length, $L_e$	0.6
Condenser length, $L_c$	0.2
Diameter of heat pipe, $D_{hp}$	0.016
Vapor core radius, $R_v$	0.0055
Wick thickness, $t_w$	0.00091
Wall thickness, $t_o$	0.00159

Table 6.

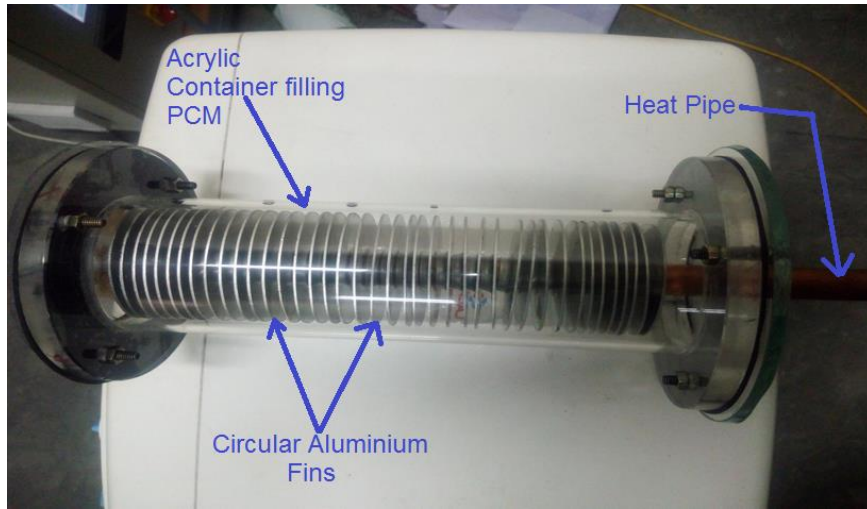
<b>S. No.</b>	<b>Parameter</b>	<b>Instrument Used</b>	<b>Range</b>	<b>Accuracy</b>	<b>%Uncertainty</b>
1.	Flowrate	Rotameter	1-10 LPH	$\pm 0.2$ LPH	$\pm 0.1$
2.	Temperature	RTD	0-500 °C	$\pm 0.5$ °C	$\pm 0.25$
3.	Solar radiation	Pyranometer	0 – 4000 W/m <sup>2</sup>	$\pm 5$ W/m <sup>2</sup>	$\pm 2.5$



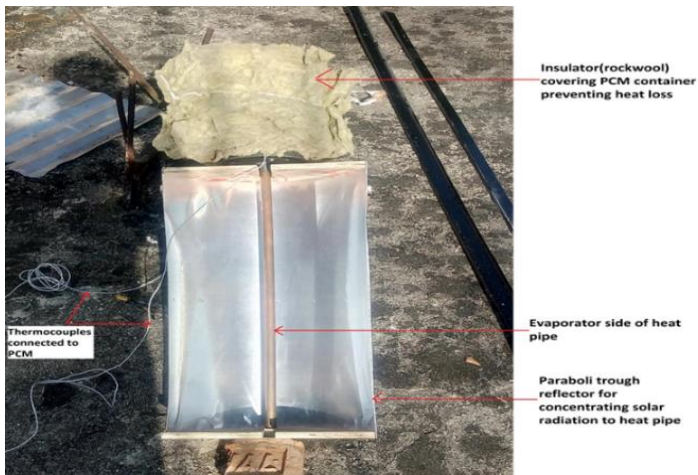
Table 7.

Sr. No.	Component	Total weight (kg)		Energy density (kWh/Kg)	Total embodied energy (kWh)	
		Case-I (TES without Fin)	Case-II (TES with Fin)		Case-I	Case-II
1.	Paraffin wax	0.60	0.60	198.3	118.98	118.98
2.	Heat pipe	1.44	1.44	19.61	28.2384	28.2384
3.	Aluminum (PTC and fin)	0.90	1.10	55.28	49.752	60.808
4.	Acrylic sheet (sheet and plate)	0.20	0.20	27.78	5.556	5.556
5.	Rockwool	0.10	0.10	6.11	0.611	0.611
6.	Rubber gasket	0.10	0.10	3.27	0.327	0.327
7.	Thermal epoxy	0	0.05	21.66	0	1.083
8.	Silicon adhesive	0.10	0.10	2.80	0.28	0.28
9.	Iron (nut-bolt, flange and support stand)	5	5	8.89	44.45	44.45
				<b>Total</b>	<b>248.2</b>	<b>260.3</b>

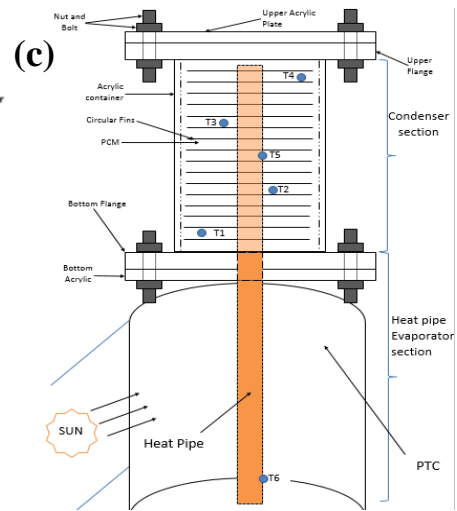
(a)



(b)



(c)



(d)

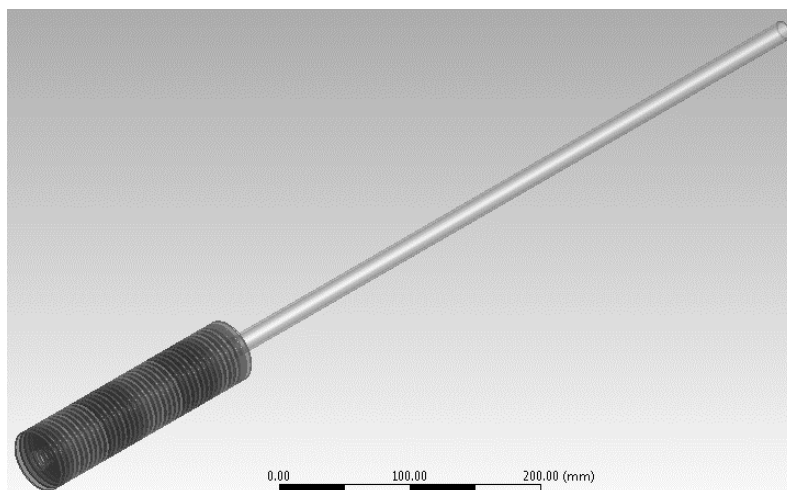


Fig. 1.

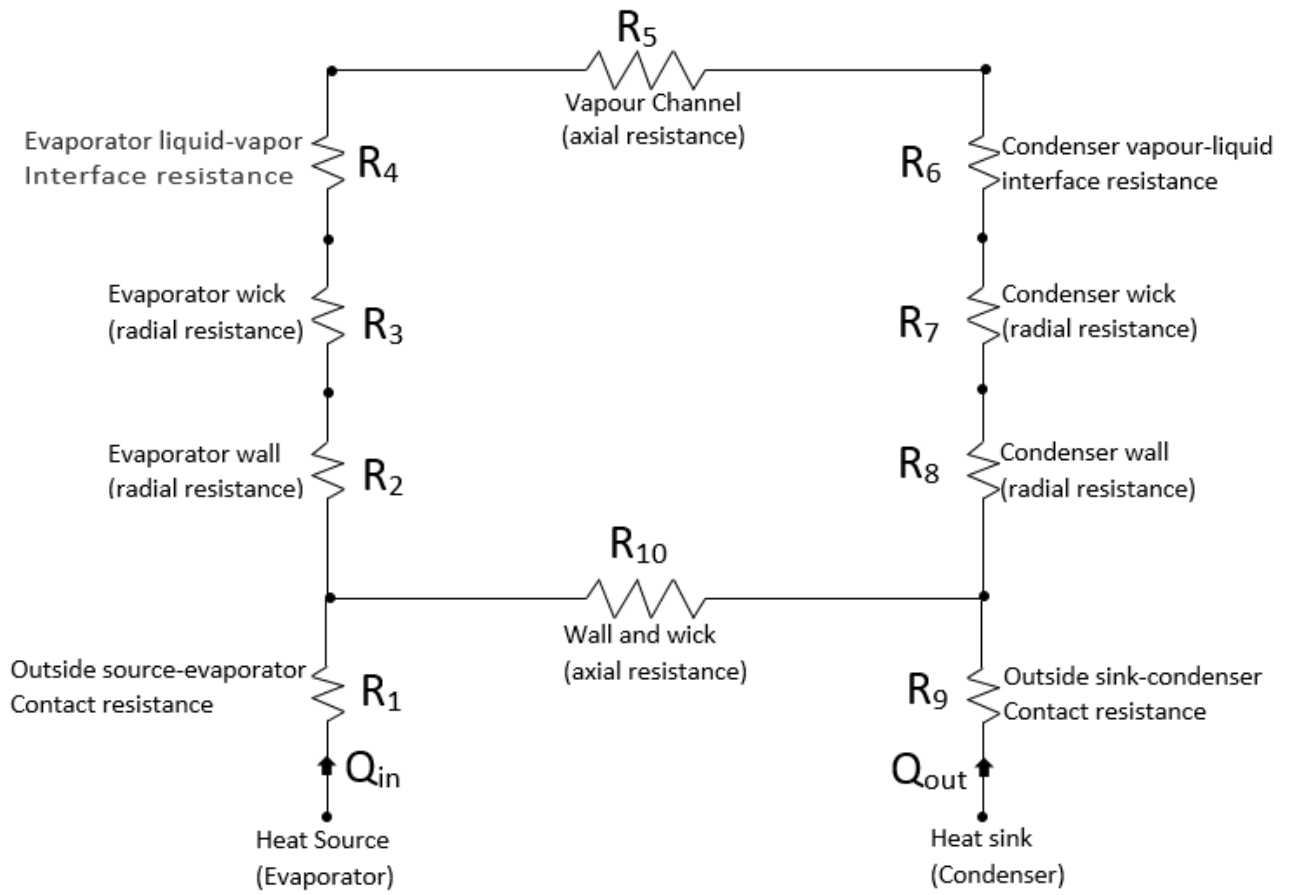


Fig. 2.

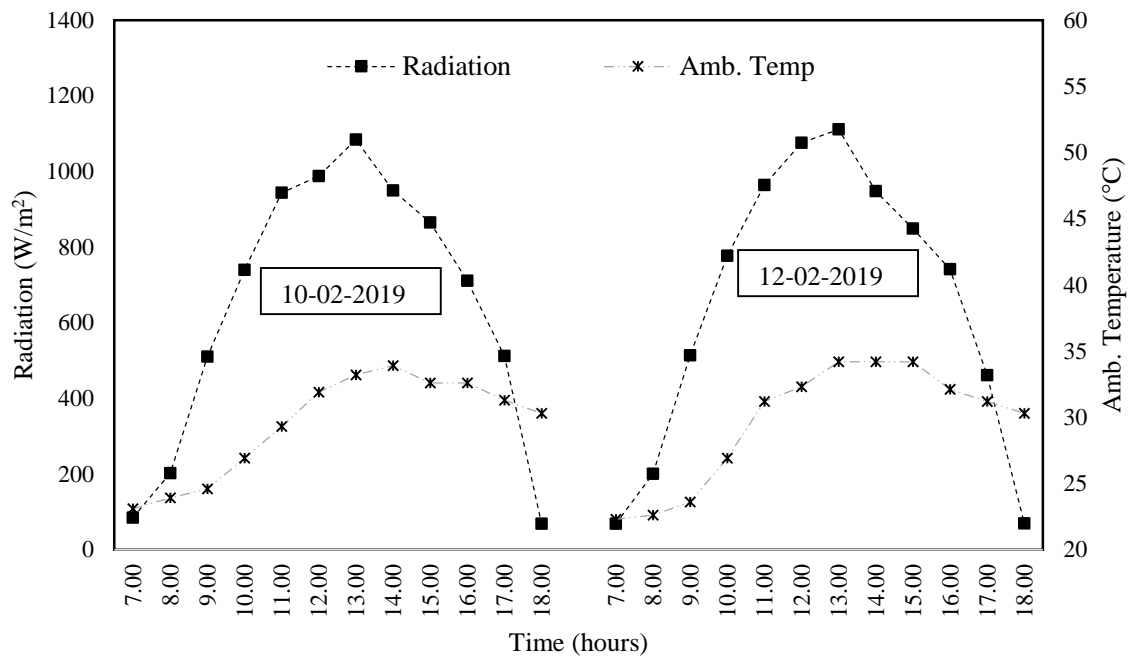


Fig.3

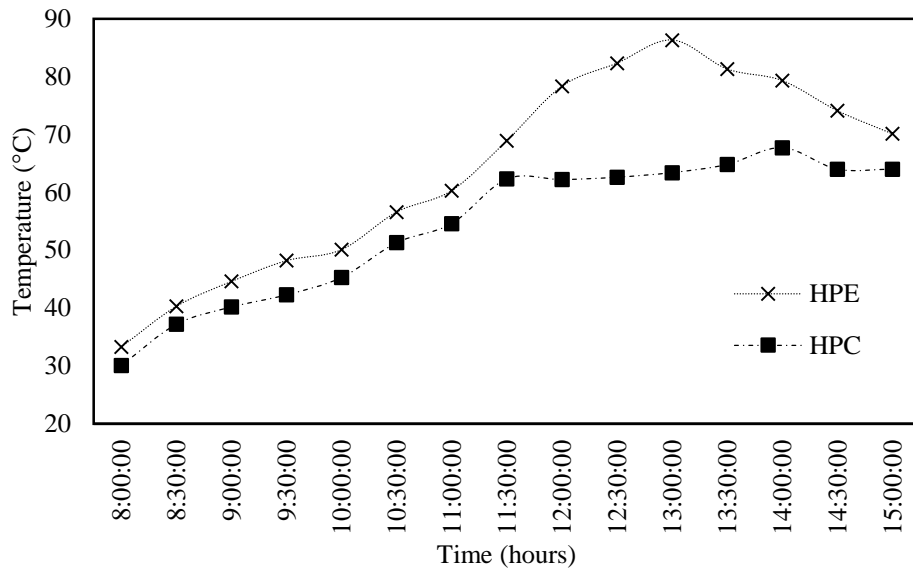


Fig. 4.

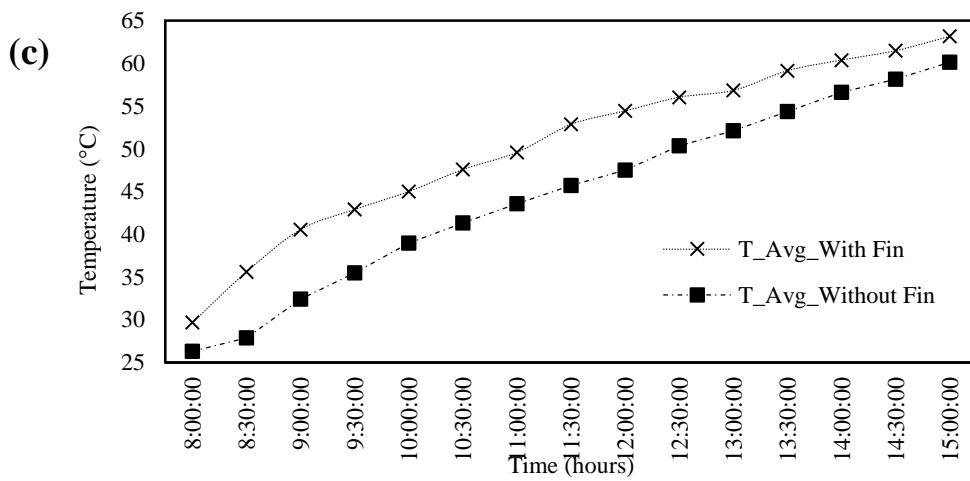
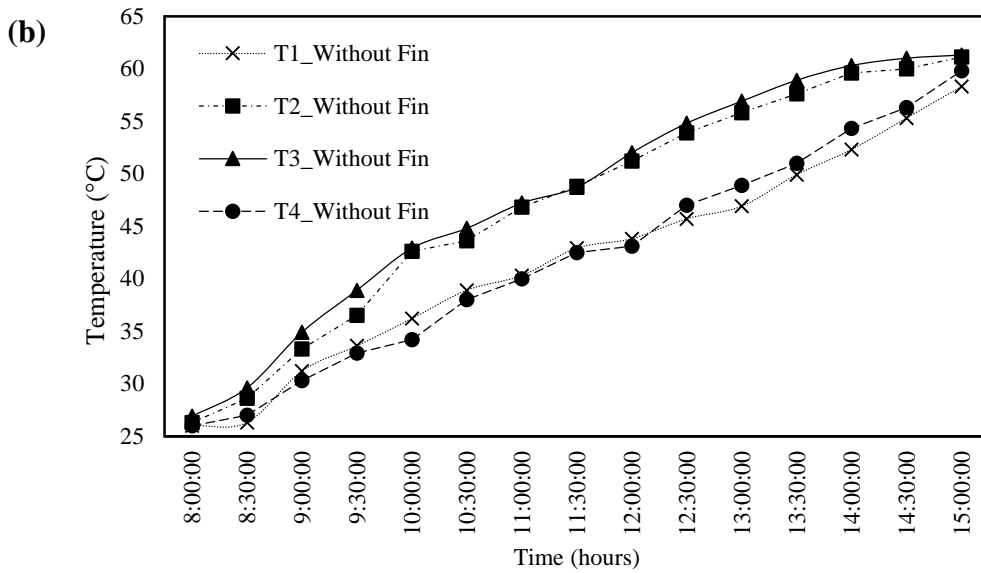
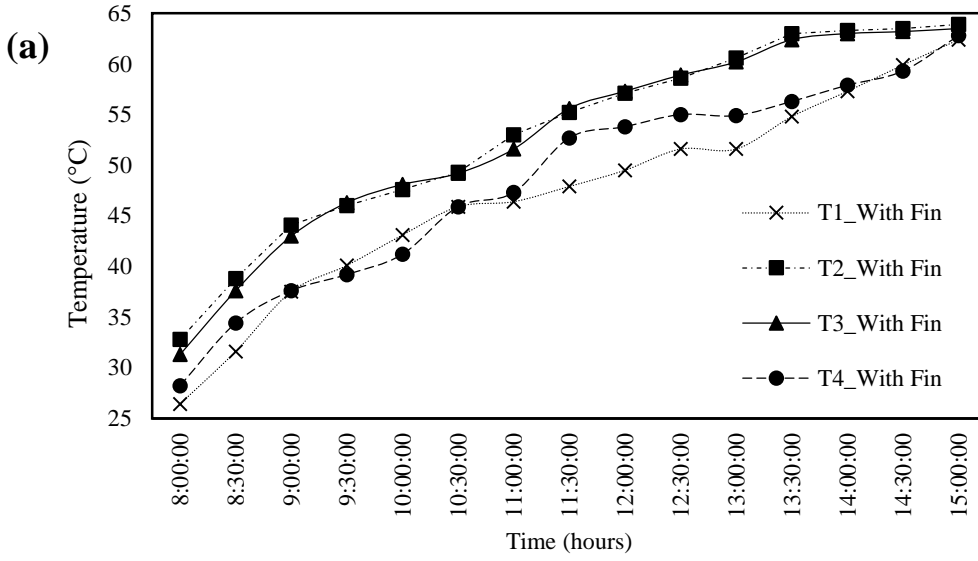


Fig. 5.

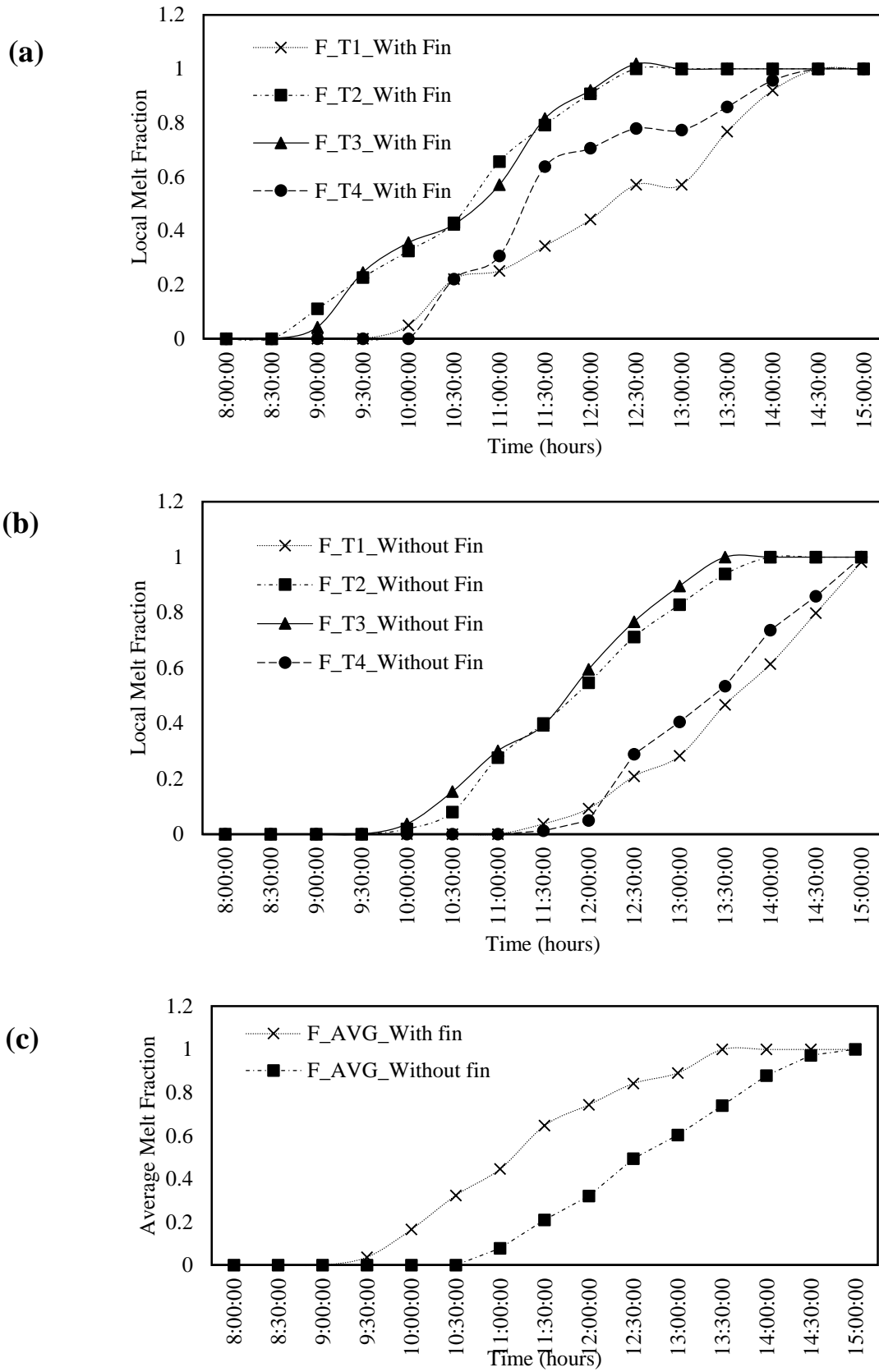


Fig. 6.

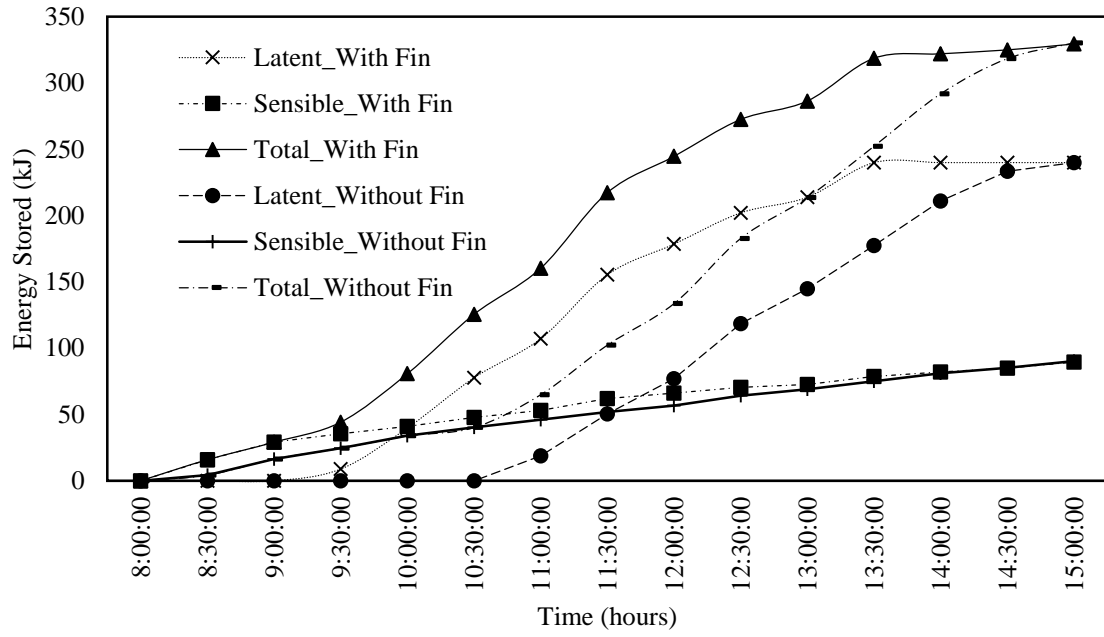
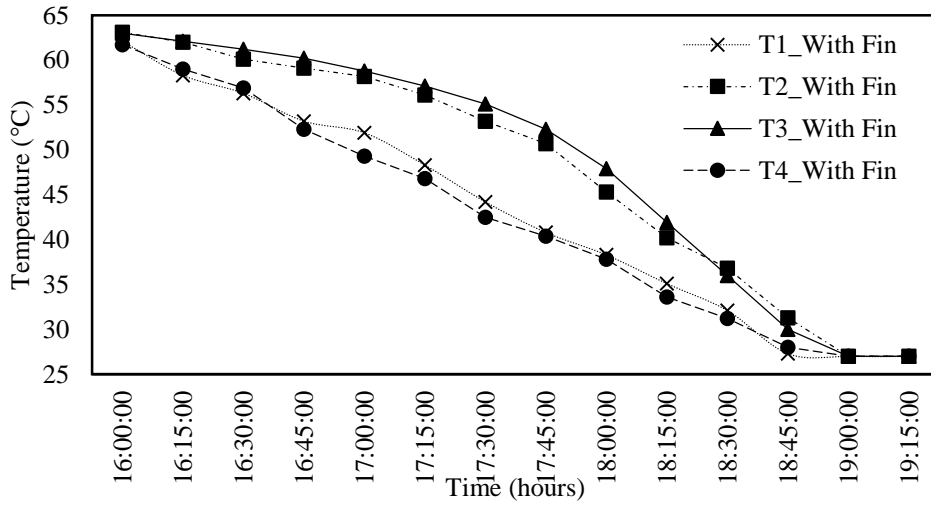


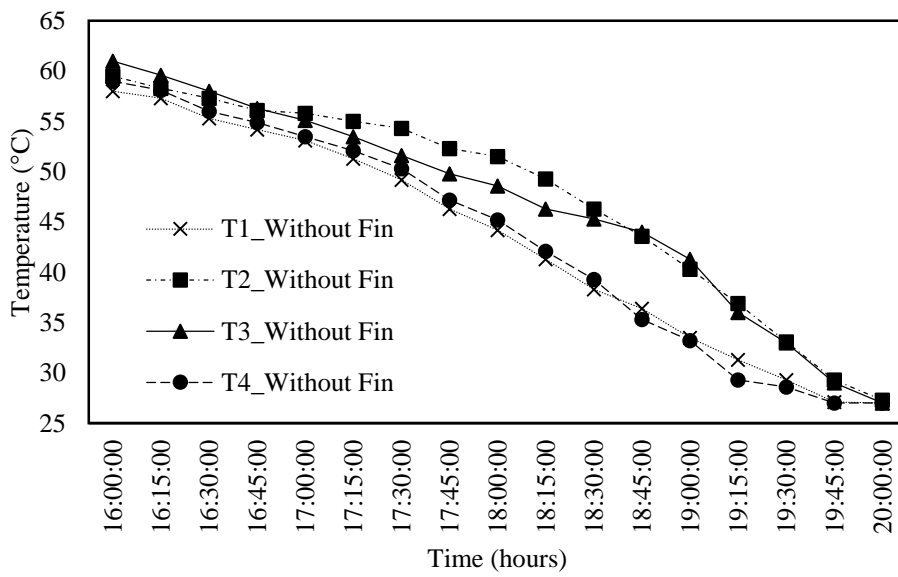
Fig. 7.



(a)



(b)



(c)

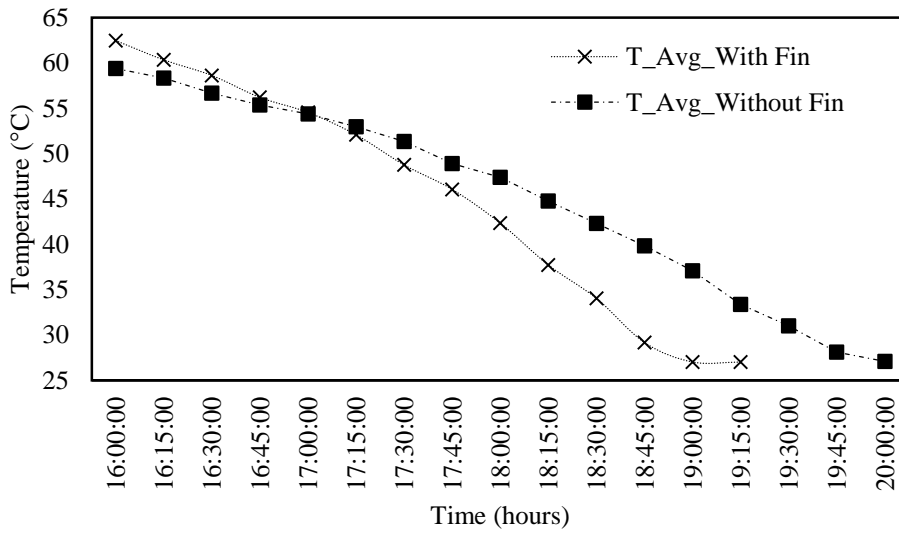


Fig. 8

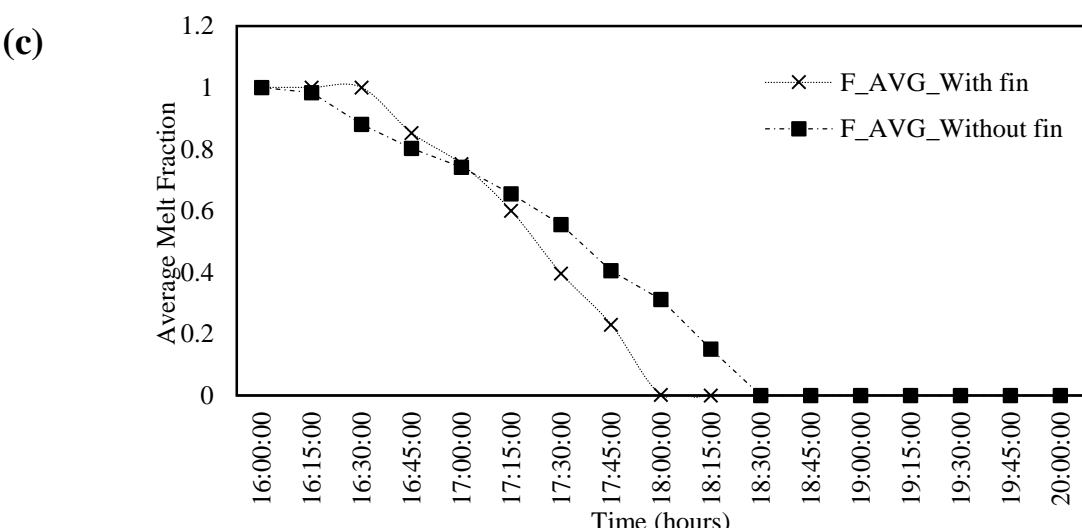
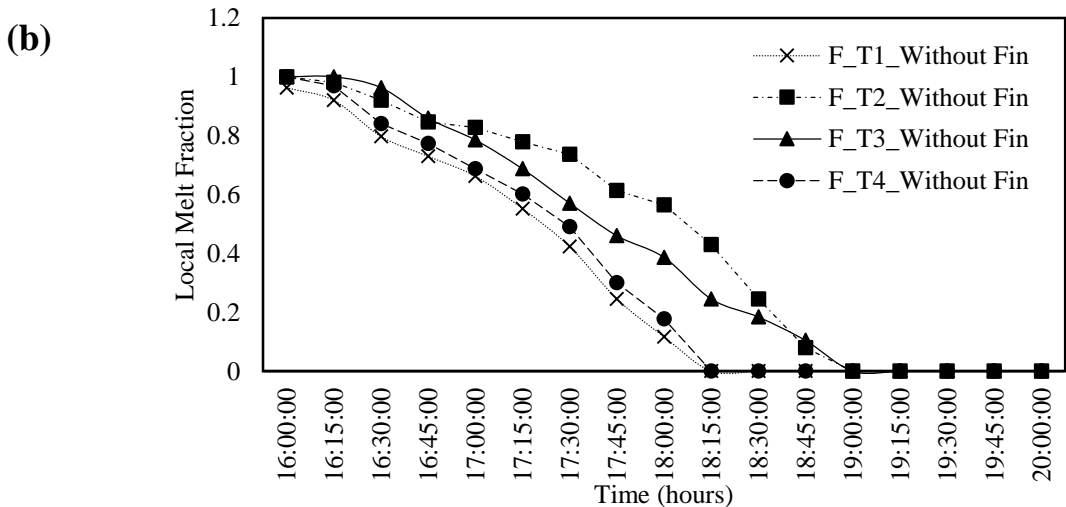
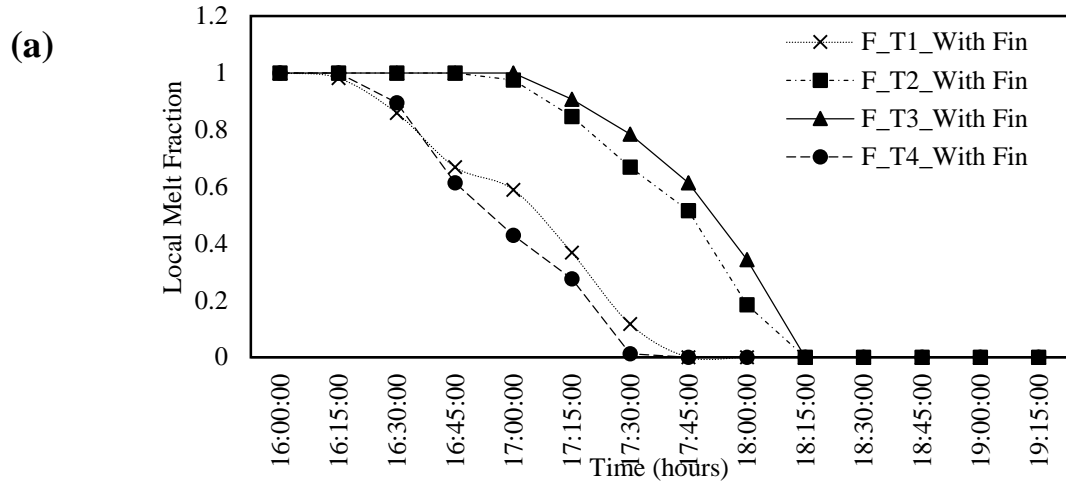


Fig. 9

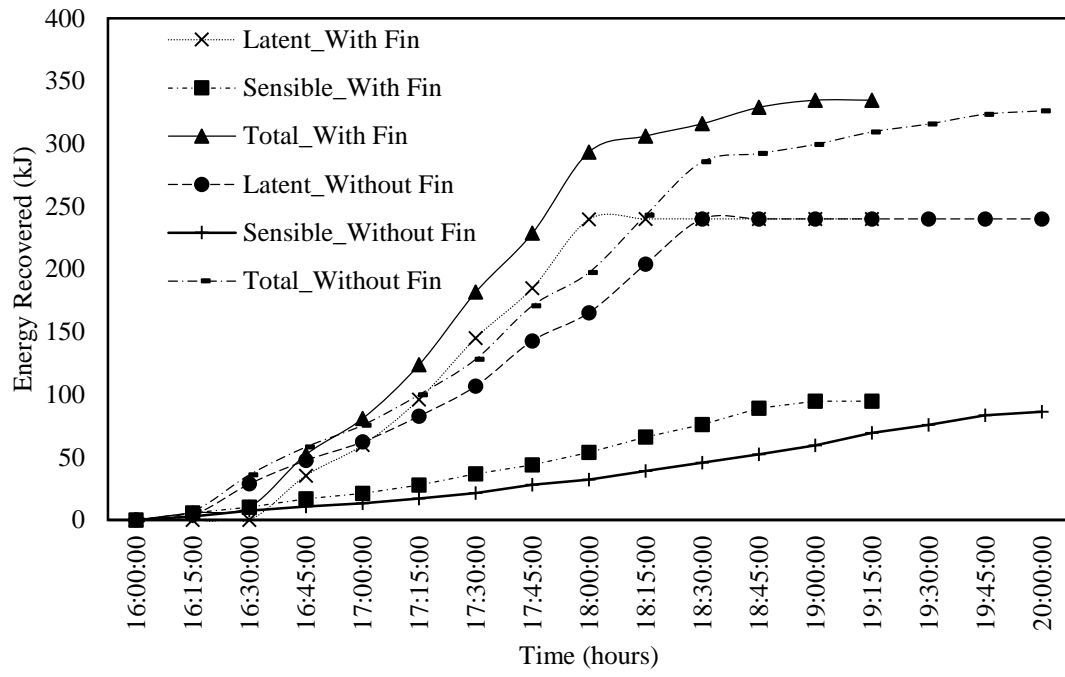


Fig. 10

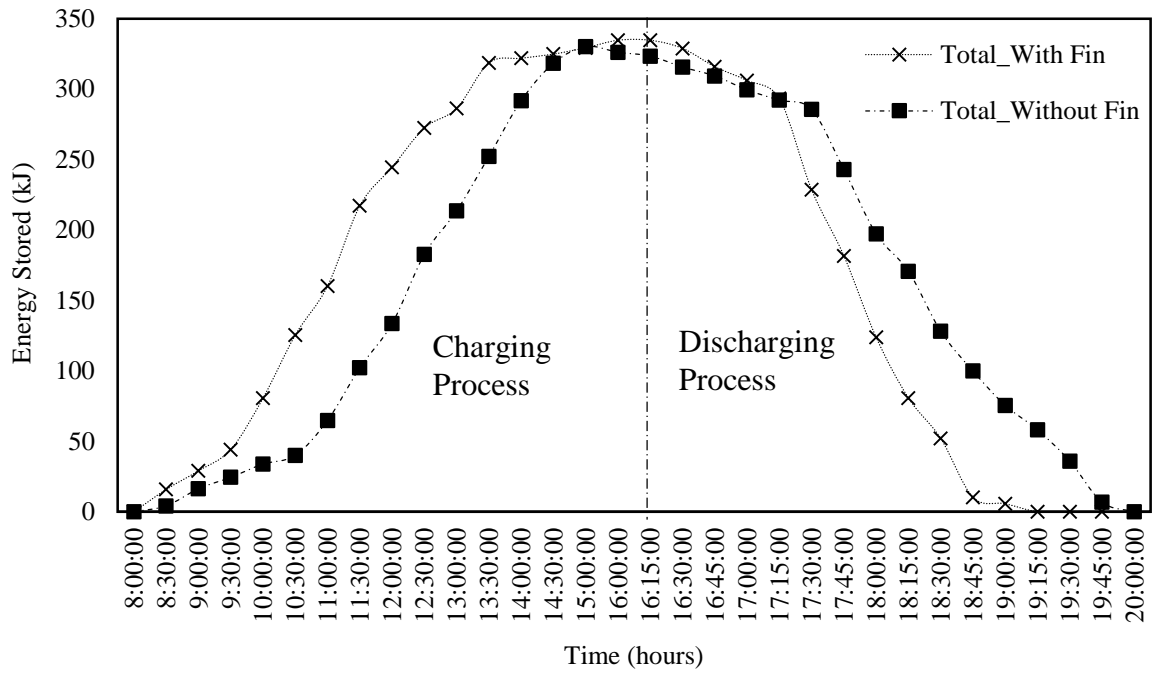


Fig.11

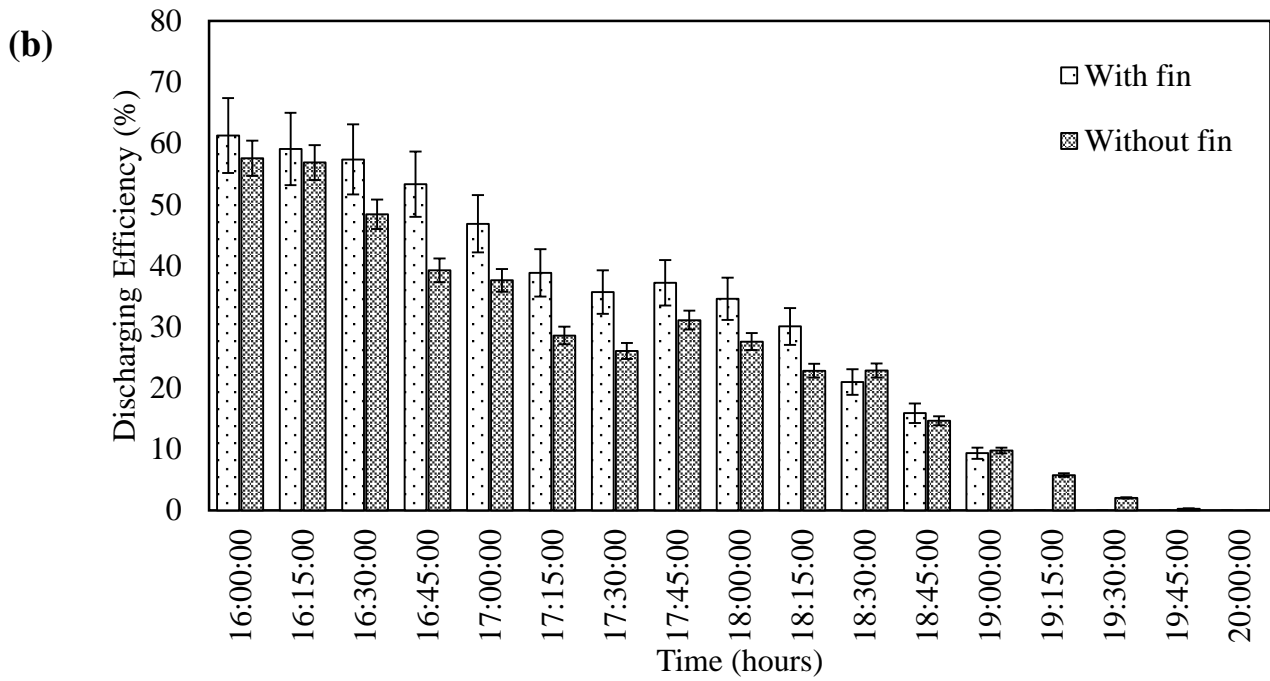
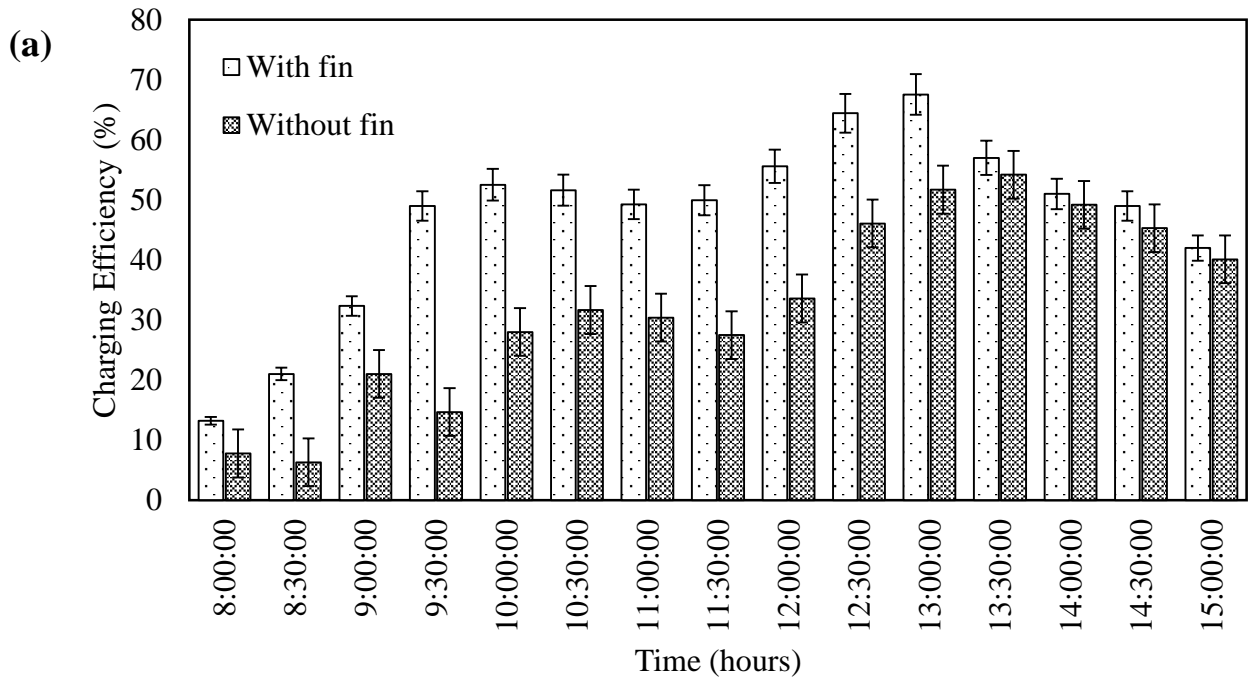


Fig. 12.

## **Conflict of Interest**

This is to declare that there is no conflict of interest with the present results.

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### **Authorship contributions**

Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., Y.L. Cheung). The name of each author must appear at least once in each of the three categories below.

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acquisition of data: \_\_\_\_\_, \_\_\_\_\_, \_\_\_\_\_, \_\_\_\_\_;

analysis and/or interpretation of data: \_\_\_\_\_, \_\_\_\_\_, \_\_\_\_\_, \_\_\_\_\_.

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